

ELECTRONIC FUNDAMENTALS

THEORY LESSON 36

PRINCIPLES OF FREQUENCY MODULATION

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Theory Lesson 36

INTRODUCTION

Up to this time, you have been studying a system in which the transmitted signal is amplitude modulated. Another type of modulation is called *frequency modulation*. In this system, the *frequency* of the modulated carrier changes in accordance with the audio intelligence. With a frequency-modulation system, a much greater reduction in noise and interference becomes possible.

A large number of FM radios are manufactured every year. You'll no doubt be called on to repair some of these sets in your future career. A thorough knowledge of the FM system will help you service these sets more efficiently.

Your knowledge of FM theory will also prove helpful if you should decide to do service work on FM communication systems. Systems of this kind are used in various industries (mining, for instance); they are also employed by the police and fire departments of different cities.

36-1. REVIEW OF AMPLITUDE MODULATION

A review of the amplitude modulation system will help us understand FM.

Let's first refresh our memory about what modulation is, why it is necessary, and the different ways in which it may be achieved.

Definition of Modulation. Modulation is the process by means of which a carrier wave is varied in accordance with another signal. This signal is known as the *modulating signal*. In radio broadcasting, modulating signals are audio-frequency waves representing speech or music.

Need for Modulation. Why is modulation necessary? Why can't we transmit the audio signals generated at the broadcast studio directly without first impressing them on a carrier?

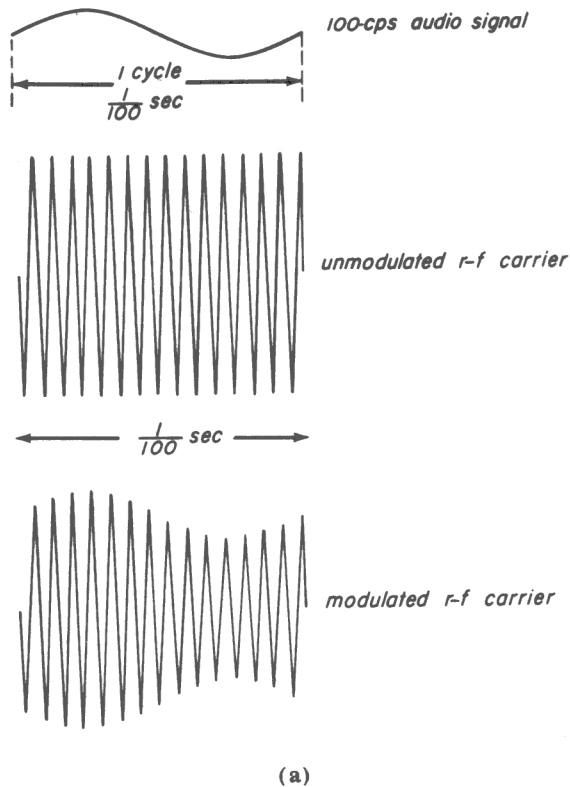
There are at least two reasons why such a procedure is impractical. In the first place, audio signals cannot readily be radiated into space. Very high-powered, expensive transmitters would be required to transmit them, and the distance over which the audio signals could be sent would be relatively small compared to the distances spanned by r-f signals.

The direct transmission of audio signals would make simultaneous operation of several stations in any one locality impossible. There is only one audio frequency range (20 to 20,000 cps, approximately). Therefore, one station alone could transmit at any given time in the service area of the audio transmitter. On the other hand, when r-f carriers of different frequencies are used, many stations can broadcast at the same time.

Methods of Modulation. Three methods of modulation are employed in radio broadcasting: amplitude, frequency, and phase modulation. The first two methods are in common use.

Information regarding two basic characteristics of an audio signal — its amplitude and its frequency — must be conveyed by the system of modulation used.

In the case of amplitude modulation, the envelope of the modulated carrier varies in accordance with the amplitude and frequency of the audio signals (Fig. 36-1a).



In frequency modulation, frequency variations in the modulated carrier are produced that are proportional to the amplitude of the audio signal; the rate or speed at which these variations take place corresponds to the frequency of the audio signal (Fig. 36-1b).

In phase modulation, the amplitude of the audio signal produces proportional changes in the phase of the modulated carrier; the rate at which these phase changes occur is the same as the frequency of the audio signal (Fig. 36-1c).

Heterodyning Process in Modulation. The most important fact relating to modulation — not merely amplitude modulation, but all modulation systems used in broadcast systems — is the following. If signals of two different frequencies are applied to a tube (or similar device) that is being operated along a nonlinear portion of its $e_c - i_b$ curve, sum and difference frequencies will be created. When two signals applied to such a tube have, say, frequencies of 2 and 3 mc respectively, the sum and difference frequencies generated will be 5 mc ($3 + 2$ mc) and 1 mc ($3 - 2$ mc).

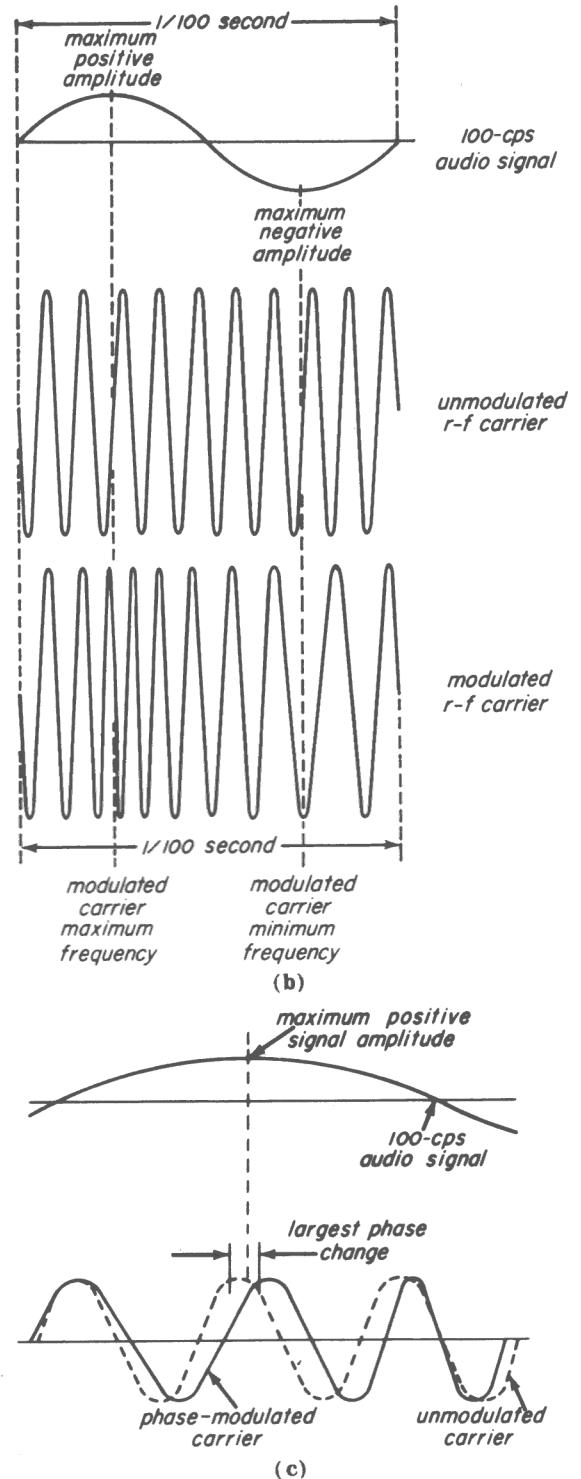


Fig. 36-1

Mixer stages are intentionally operated in such a way that they operate along a nonlinear section of the $e_c - i_b$ curve. This permits the heterodyning process just described to take place.

In an amplitude-modulation system, the range of the audio modulating signals is

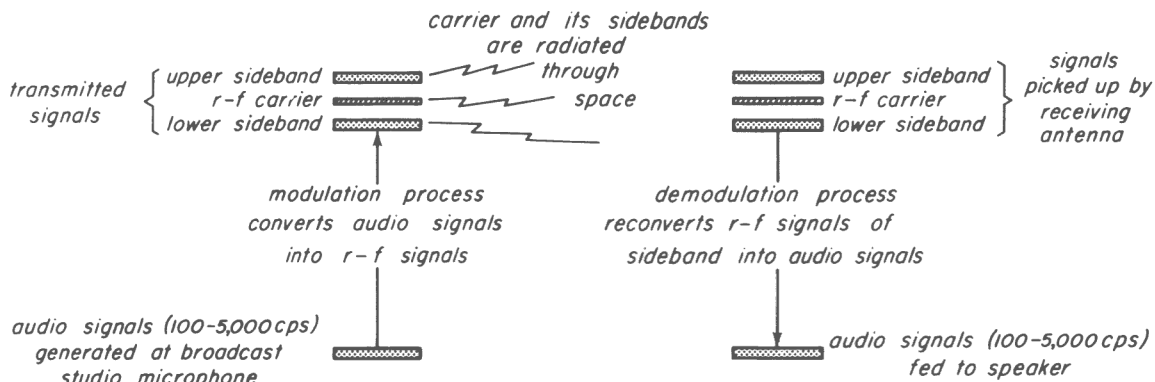


Fig. 36-2

most often 100 to 5,000 cps. These signals must be raised to much higher frequencies for transmission purposes (see Fig. 36-2). To achieve this, the audio signals are heterodyned with a carrier wave in a mixer tube.

An illustration of what happens to a single frequency will help us understand what happens to them all. If we beat an audio signal of 1 kc with an r-f carrier of 570 kc, heterodyne or beat frequencies of 571 kc ($570 \text{ kc} + 1 \text{ kc}$) and 569 kc ($570 \text{ kc} - 1 \text{ kc}$) will be produced. These new signals are called *sideband frequencies*. They contain the same audio information as the original 1-kc signal.

When signals representing the different frequencies in the audio range (100 to 5,000 cps) heterodyne with the r-f carrier, beat-frequency signals ranging from 570,100 cps ($570,000 + 100 \text{ cps}$) to 575,000 cps ($570,000 + 5,000 \text{ cps}$) will form one complete sideband; signals ranging from 569,900 cps ($570,000 - 100 \text{ cps}$) to 565,000 cps ($570,000 - 5,000 \text{ cps}$) comprise the other sideband.

Note that identical audio information is contained in each sideband; only one of the two sidebands is needed at the receiver, even though both are transmitted.

The r-f carrier and its sidebands are stepped down to intermediate frequencies in the receiver. The i-f carrier beats against both sets of i-f sideband signals in the 2nd detector. The original audio signals are reproduced as a result of this heterodyning process.

Consider the 1-kc audio signal that was changed into radio frequencies of 571 and 569 kc at the transmitter. The radio frequencies are stepped down to 454 and 456 kc in the converter stage of the receiver. (An intermediate frequency of 455 kc is assumed.) The heterodyning of the 454-kc sideband with 455-kc carrier reproduces the original 1-kc audio signal; so does the heterodyning of the 456-kc sideband signal and the 455-kc carrier. Since the audio signal is reproduced in duplicate, so to speak, it is larger in amplitude than it would be if only one sideband was applied to the 2nd detector. Other signals in the audio range are reproduced in a similar fashion. We are taking time to review this process in detail because it will help us understand the more complicated heterodyning process that takes place during the mixing of signals in an FM system.

It is frequently assumed that the amplitude of the carrier (alone) varies in amplitude modulation. *This is not true.* The carrier amplitude merely seems to vary. Actually, the amplitude of the carrier is constant; *it is the amplitude of the composite wave — the carrier plus its two sidebands — that varies.*

Figure 36-3 shows a modulated r-f carrier. The modulated carrier is made up of the unmodulated carrier (sketch *b*) and the upper and lower sidebands (sketches *c* and *d*). The sidebands shown are the result of the heterodyning of the r-f carrier with an audio signal at some instant. The situation has been simplified by considering that a single, constant-amplitude audio signal

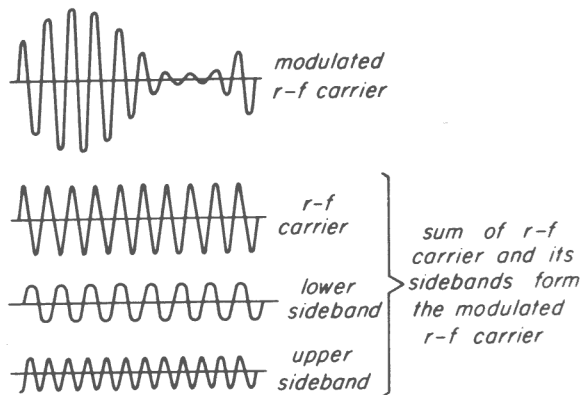


Fig. 36-3

is being transmitted at this instant. If the amplitudes of the r-f carrier and its sidebands were added from instant to instant — if, in other words, we plotted a graph showing what the sum of the three signals was at successive, closely-spaced times throughout several cycles — the waveform shown in *a* would result.

The amplitude of the *unmodulated* carrier is *not* varied by the modulating signals. The amplitude of the *modulated* carrier (the unmodulated carrier plus its two sidebands) *does* vary in accordance with audio signals. The amplitude of the *sideband* signals varies in step with the amplitude of the audio signals that produce them.

Another important point: At 100% modulation, which is the maximum amount of modulation possible without distortion, the voltage amplitude of each sideband is 50% as large as the carrier (Fig. 36-4).

Of the total power present in the modulated carrier, 16-2/3% is in each sideband; 66-2/3% of the power is in the carrier. Since the carrier carries no intelligence, 66-2/3% of the power generated by the transmitter is wasted. This is an indication

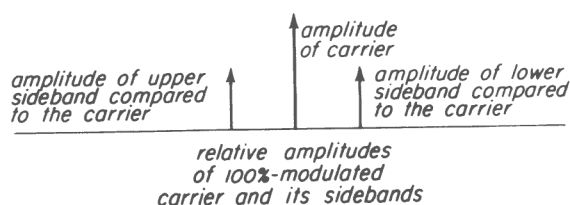


Fig. 36-4

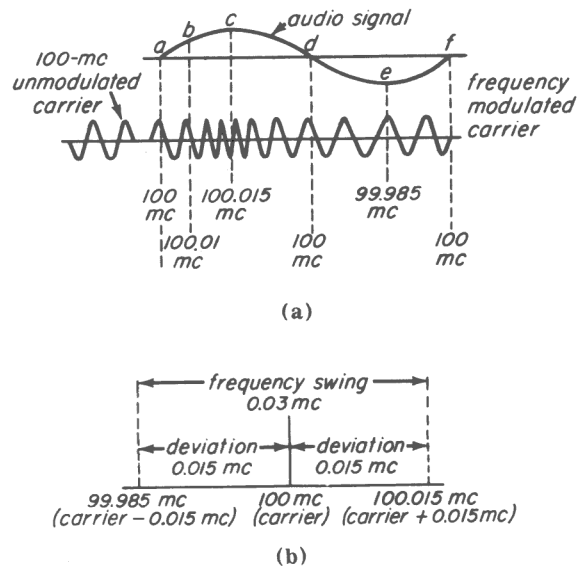


Fig. 36-5

of the inefficiency of an amplitude modulation system.

Most AM stations transmit sidebands that occupy 5 kc of spectrum space either side of the carrier. These sidebands represent audio frequencies extending to 5,000 cps. The tuned circuits of the AM receiver must have a bandpass of at least 10 kc to accept the carrier and its two sidebands.

36-2. ABC'S OF FREQUENCY MODULATION

In a frequency modulation system, the amplitude of the modulated wave remains constant while its frequency varies. We won't consider, just now, *how* the frequency modulation is produced. Let's just see what the *effect* of the process is on the FM carrier.

Assume that the audio signal shown in Fig. 36-5a is to modulate a 100-mc r-f carrier. As the audio signal rises in amplitude from point A to point C, the frequency of the modulated carrier rises by 0.015 mc. The audio signal is its peak at point C. The frequency of the modulated carrier is 100.015 mc at this time. As the audio signal decreases in amplitude (point C to D), the frequency of the modulated carrier decreases. At the zero level of the audio signal, the frequency of the modulated carrier is back at 100 mc. When the audio signal increases in the negative direction (points D to E),

the frequency of the modulated carrier falls to 99.985 mc; as the audio signal returns from its negative peak to the zero level, the frequency of the modulated carrier comes back to 100 mc.

A complete back-and-forth movement of the modulated carrier from the center or *resting frequency*, to the maximum deviation frequency in one direction, back to the resting frequency, then to the maximum deviation in the other direction, and finally back to the resting frequency is called a *frequency swing*. *Frequency deviation* is the term used to describe the movement of the carrier from resting frequency to one side of the carrier alone (Fig. 36-5b). *Note that the largest frequency deviation is produced when the amplitude of the audio signal is maximum.*

We have just seen how the amplitude characteristic of the audio signal is converted into a frequency deviation. What about the frequency characteristic of the audio signal? Information regarding this characteristic must also be passed on to the modulated carrier if it is to effectively represent the intelligence present in the audio signal.

The frequency characteristic of the audio signal affects the *rate* at which the frequency deviations of the modulated carrier occur. If the audio signal is a 100 cps note, the frequency swings or excursions of the modulated carrier will occur 100 times a second; if the signal has a frequency of 1,000 cps, these excursions will take place 1,000 times a second, etc. If the amplitude of the 100 cps signal is equal to that of the 1,000 cps signal, the *amount* of frequency deviation will be the same in both cases, although the *rate* at which these deviations occur will be different.

In the receiver, the reverse of the process occurring at the transmitter takes place. The frequency deviations of the modulated carrier are applied to a detector tube. The output of the tube varies in *amplitude*, in proportion to the incoming signal's variation in *frequency*. The larger the deviation of the incoming signal from the frequency of the unmodulated carrier, the

greater is the amplitude of the output of the FM detector. The amplitude characteristic of the original audio signal is recovered in this way.

No special process is required to regain the frequency characteristic since this characteristic undergoes no change. To clarify this, let's assume that a 100 cps audio signal with a peak-to-peak amplitude of 2 volts has caused the modulated r-f carrier to swing from 100 mc, to 100.0001 mc, to 99.9999 mc, and back to 100 mc. The frequency deviation is 0.0001 mc. The rate at which the deviation occurs is 100 cps. At the FM detector in the receiver, the 0.0001-mc frequency deviation produces an output amplitude variation with a peak-to-peak voltage of 2 volts. The rate at which this amplitude variation occurs is the same as that of the frequency deviation which produced it — 100 cps. The frequency characteristic of the audio signal, which has been passed on from the original audio signal to the modulated carrier, is thus retained in the demodulated audio signal.

Simple Method of Producing Frequency Modulation. A simple way of producing frequency modulation is illustrated in Fig. 36-6a. While this is not the method used to produce an FM signal in practice, a discussion of it will help us understand the

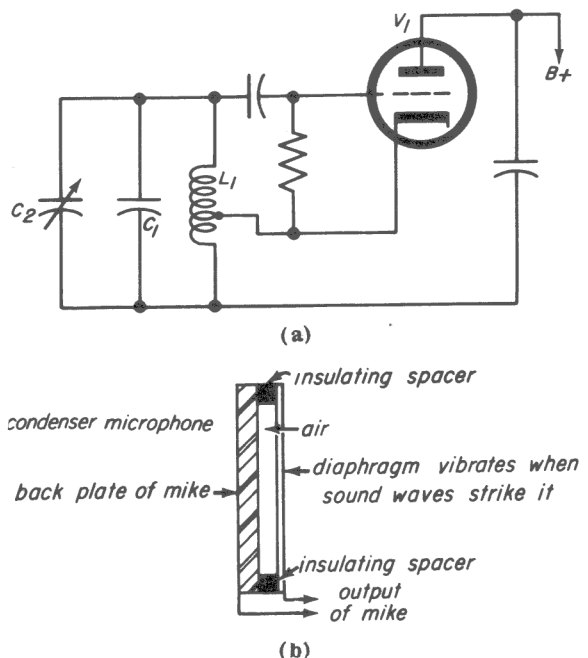


Fig. 36-6

more complicated manner in which FM signals are actually generated.

The tube V_1 and the components associated with it comprise a Hartley r-f oscillator. L_1 and C_1 form the tuned circuit. C_2 represents a condenser microphone (Fig. 36-6b). The diaphragm of the microphone is movable, making C_2 , in effect, a variable capacitor. Sound waves directed at the microphone cause the diaphragm to vibrate back and forth; therefore the spacing between the plates of C_2 varies, causing the capacitance of C_2 to change.

At any instant, the capacitance of C_2 depends on the loudness of the sound directed against the microphone. A loud sound will cause a large back-and-forth movement of the C_2 variable plate, causing a large variation in the capacitance of C_2 ; a low-amplitude sound will cause a small variation in the capacitance of C_2 . Since C_2 is in parallel with C_1 , variations in the capacitance of C_2 will cause the oscillator frequency to vary. Amplitude variations in the sound thus produce frequency variations of an r-f carrier (if we consider the output of the oscillator when no sound is being directed against the microphone as the carrier signal).

The frequency of the sound signal controls the rate at which the condenser microphone diaphragm varies back and forth, or the rate at which changes in the capacitance of C_2 take place. This is, in turn, the same rate at which changes in the oscillator frequency occur. The frequency characteristic of the audio signal is thus transferred to the modulated r-f carrier.

Practical Frequency Modulation Circuit.

A simplified version of a circuit actually used for frequency modulation is shown in Fig. 36-7. The oscillator is similar to the one discussed in the preceding section. However, the oscillator frequency is not varied by a condenser microphone, but by a device known as a *reactance tube*.

A reactance tube is a tube whose circuit is such that plate current lags or leads the plate voltage. If the current *lags* the plate

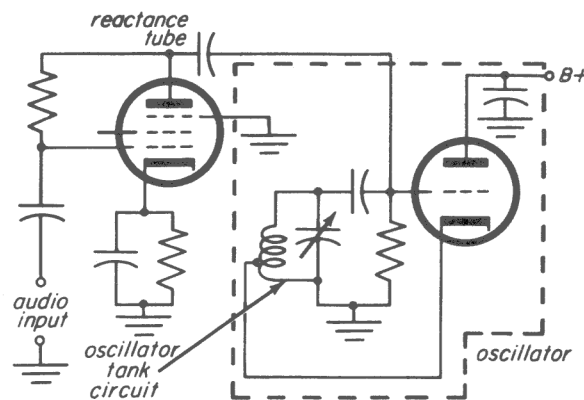


Fig. 36-7

voltage, the tube acts like a capacitive reactance. If the plate current *lags* the plate voltage, the tube acts like an inductive reactance.

The reactance tube circuit used in frequency-modulation transmitter systems is often connected to act like an inductive reactance. When the tube is connected in parallel with a coil, the inductive reactance of the circuit is not merely that of the coil, but of the coil and tube in parallel. The tube acts like a second coil in parallel with the first one.

The reactance tube, as the name implies, is a tube that possesses reactance. Furthermore, the reactance can be altered without changing the frequency of the applied voltage (as would be required in a real inductance). Consider the following formula:

$$X_L = \frac{e_p}{i_p \angle -90^\circ}$$

If e_p remains constant, and if i_p can be made to vary, the inductive reactance can vary. In a reactance tube, the amount of inductive reactance can be varied by changing the control-grid-to-cathode voltage. The reactance can be varied at an audio rate by applying the audio signal to the control grid of the reactance tube. When the audio signal moves in the positive direction, the grid-cathode voltage of the tube decreases; the plate current will increase, and the inductive reactance of the tube will decrease. When the a-c signal at the grid

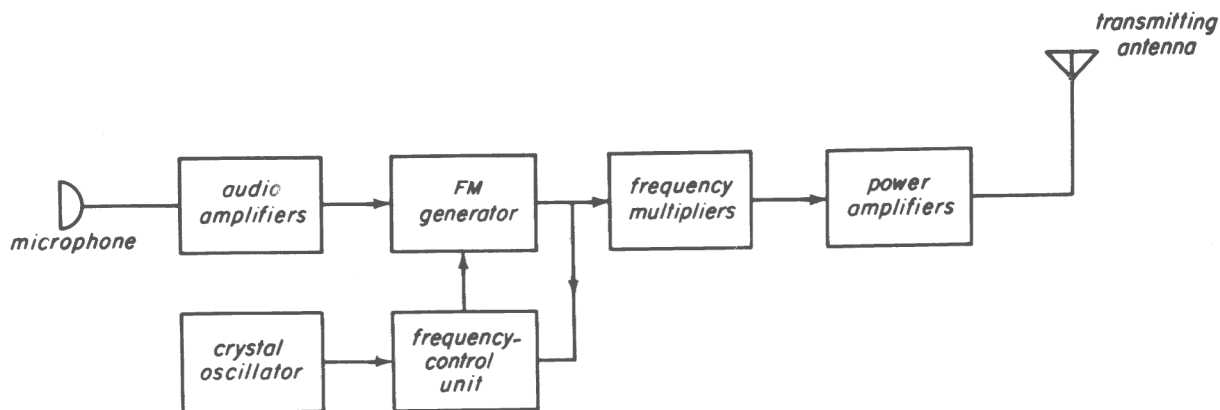


Fig. 36-8

moves in the negative direction (or becomes less positive), the a-c plate current flow drops. Therefore, the inductive reactance of the tube rises.

Changes in the amplitude of the audio signal thus produce corresponding variations in the inductive reactance of the reactance tube. Since this reactance is in parallel with the tuned circuit, the oscillator frequency is changed when it varies. When the audio signal rises in amplitude in the positive direction, plate current increases and the inductive reactance of the reactance tube decreases, the net inductive reactance in the tuned circuit decreases, and the oscillator frequency rises. When the audio signal moves in the negative direction, causing the bias to rise, the plate current decreases, the inductive reactance of the reactance increases, the net inductive reactance in the tuned circuit increases, and the oscillator frequency falls.

Amplitude changes in the audio signal are thus converted into frequency variations of the oscillator signal. The rate at which these frequency variations occur is the same as the frequency of the audio signal. The essential requirements of the FM process are thus satisfied.

36-3. FM TRANSMITTER OPERATION

Familiarity with the entire FM system, including the FM transmission process, will give you the perspective needed for a thorough understanding of the operation and servicing of FM receivers. Let's con-

sider what goes on in a representative FM transmitter. A block diagram of an FM transmitter is shown in Fig. 36-8.

The *audio amplifier* section amplifies the weak audio voltages generated by the microphone at the broadcast studio. These audio signals are amplified to the levels needed for effective modulation.

The FM generator section comprises an oscillator and a reactance modulator. The oscillator creates the r-f carrier signal; the reactance modulator produces frequency changes in the oscillator that correspond to the frequency and amplitude characteristics of the audio signal.

The *frequency multipliers* are stages that increase the frequency of the r-f carrier signal generated by the oscillator. These stages also increase the small frequency deviations of the modulated r-f carrier. The maximum deviation permitted under FCC regulations is 75 kc from either side of the carrier, or a back-and-forth swing of 150 kc. The maximum swing originally produced in the FM generator section is much smaller than 150 kc.

The reason why the r-f carrier frequency is low to begin with (approximately 5 mc), and must be raised to FM channel frequency (88 to 108 mc) is that an oscillator operating in the 88 to 108 mc region would not have the stability needed for transmitter operation.

Frequency Control Stages. Even though the oscillator is operated at or near the relatively low frequency of 5 mc, it still

does not have the stability required under FCC Rules and Regulations. FCC rules stipulate that the oscillator used to generate the r-f carrier must not drift more than 2,000 cps away from its resting frequency. (The resting frequency is the frequency of the oscillator when it is unmodulated.)

To minimize oscillator drift, special correction circuits are used. These circuits contain a crystal oscillator and a frequency control unit. The crystal oscillator generates a very stable, drift-free signal whose frequency is the same as the normal resting frequency of the oscillator. The frequency-control unit compares the frequencies of the signals generated by the crystal oscillator and the oscillator in the FM generator section. If the FM oscillator drifts away from the frequency of the crystal oscillator, a voltage develops in the control unit that is proportional to the amount of oscillator drift. This voltage is fed back to the oscillator, and causes it to be brought back to the correct frequency of operation instantaneously.

The power amplifier amplifies the FM r-f signals to the high levels needed for effective transmission. When they have left the power amplifier, the FM signals are radiated by the antenna.

36-4. FM SIDEBANDS

In amplitude modulation, each audio-modulating signal creates *one* pair of sideband frequencies when it beats against the r-f carrier. In frequency modulation, *many* pairs of sideband frequencies are created when the carrier heterodynes with one audio modulating signal.

If a 1,000-cps signal modulates a 1-mc carrier in an AM transmitter, the two sideband frequencies will be 1.001 mc (1,000,000 + 1,000 cps) and 0.999 mc (1,000,000 - 1,000 cps).

If the same 1,000-cps signal modulates a 1-mc carrier in an FM transmitter, however, not two but, theoretically, an *infinite* number of sideband frequencies are generated.

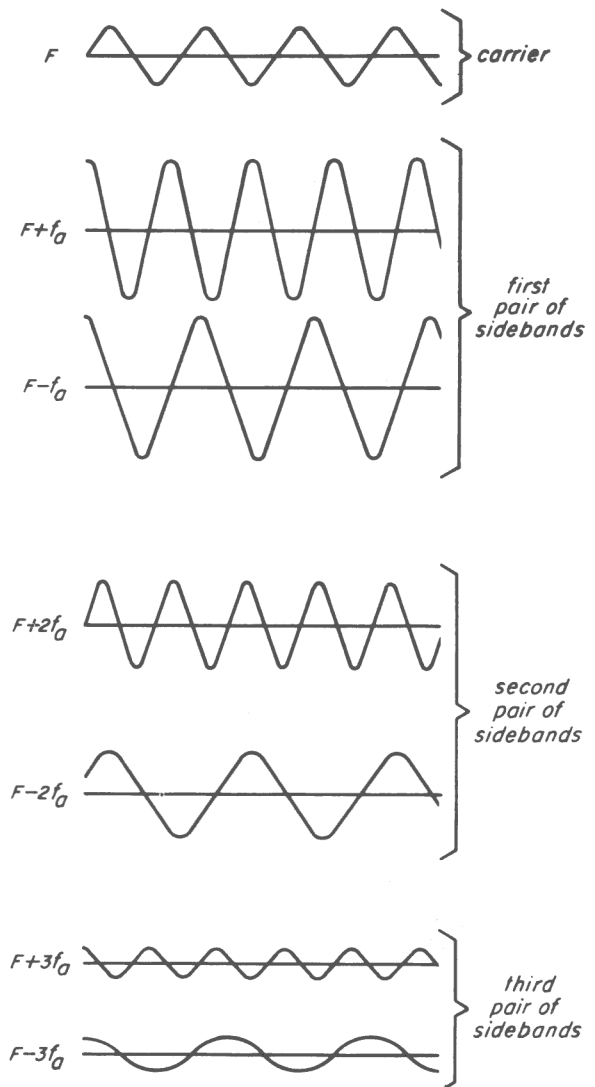


Fig. 36-9

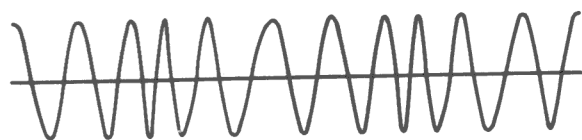
The first pair of sidebands will be the sum and difference frequencies formed by the carrier and the modulating signal. If we call the carrier frequency, F , and the modulating signal f_a , the first pair of sidebands will be $F + f_a$ and $F - f_a$ (see Fig. 36-9). In the case we have just assumed, the first pair of sidebands will be 1.001 mc (1,000,000 + 1,000 cps) and 0.999 mc (1,000,000 - 1,000 cps). The first pair of sidebands resembles the pair generated in amplitude modulation. The second pair of sidebands will be $F + 2f_a$ (the carrier plus twice the frequency of the modulating signal), and $F - 2f_a$ (carrier minus twice the frequency of the modulating signal). The frequencies in this case would be 1.002 and 0.998 mc. The third pair of sideband sig-

nals will be $F + 3f_a$ and $F - 3f_a$, the fourth, $F + 4f_a$ and $F - 4f_a$, etc.

Just as in AM, the sidebands contain the audio intelligence. The intelligence is, however, distributed over many pairs of sidebands, rather than one. If all the significant sidebands are not passed by the transmitter and receiver circuits, the FM signal will be distorted. The tuned circuits of the transmitter and receiver must therefore be wide enough to accept these sideband frequencies.

With all the significant sidebands present, the amplitude of the modulated wave will be constant at all times, and there will be no distortion (Fig. 36-10a). Figure 36-10b shows the amplitude distortion in a modulated FM wave that contains only the first pair of sidebands, and Fig. 36-10c shows the amplitude distortion in a modulated wave that contains only the first and second pairs of sidebands.

The further the sidebands extend from the carrier (see Fig. 36-11) the smaller their amplitude tends to become. (In Fig. 36-11, the fourth pair of sidebands has a great-



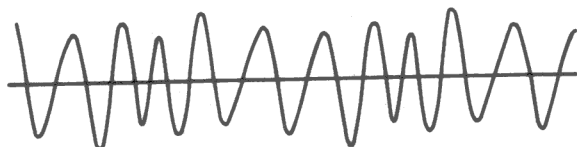
FM carrier + all sidebands

(a)



FM carrier + first pair of sidebands

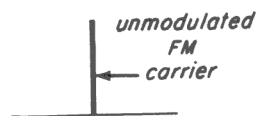
(b)



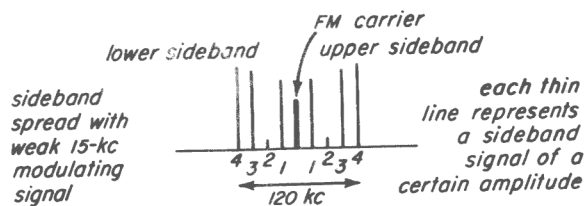
FM carrier + first and second pair of sidebands

(c)

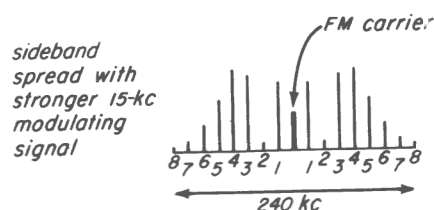
Fig. 36-10



(a)



(b)



(c)

Fig. 36-11

er amplitude than the third. But, the sideband signals in general drop off in amplitude, the greater their separation from the carrier.) After a certain point, the amplitude of the sidebands becomes negligible. So then, while the sidebands theoretically extend to infinity, as we previously pointed out, the significant or important ones are limited in number.

The first pair of sidebands is separated from the carrier by a distance equal to the modulating frequency. The second pair is separated from the carrier by a distance equal to twice the modulating frequency. The succeeding pairs of sideband signals extend, in a similar way, further and further from the carrier.

While the amplitude of the unmodulated FM carrier is normally constant at all times, the amplitude of the carrier component while modulation is taking place is constantly varying. This is so because sideband energy is derived from the carrier. The greater the energy in the sidebands, the smaller is the amplitude of the carrier, and the less power it contains. Note in Fig. 36-11 that the amplitude of the carrier (which is represented by the heavy black line) drops

as the number of sidebands increases. Much less energy is wasted in transmitting the carrier (which contains no intelligence) in FM, than is the case in AM.

In AM, the amplitude of the unmodulated carrier remains constant both before and after modulation. In FM, the amplitude of the unmodulated carrier is constant only before modulation; after modulation, the carrier amplitude constantly changes. The amplitude of the *unmodulated carrier* (carrier without sidebands) remains the same at all times.

36-5. FM BANDWIDTH CONSIDERATIONS

There is an important distinction between the bandwidth of the incoming signal and the bandwidth of the stages through which this signal passes. To avoid confusion, we'll call the range of frequencies in the FM transmission the *frequency spread*. The term *bandwidth* will be reserved for describing the bandpass characteristic of tuned stages.

In AM, the bandwidth of the receiver tuned circuits should be large enough to accommodate the frequency spread of the incoming signal. The maximum frequency spread of the transmitted signal is limited to about 10 or 15 kc, and the receiver tuned circuits have a bandwidth of about 10 or 15 kc. Thus, the complete range of sideband signals, representing all the audio information in the AM transmission, is accepted by the receiver. In FM, the frequency spread of the transmitted signal may extend beyond the spectrum space assigned to the FM channel.

In AM, the frequency spread of a station signal depends on the range of audio frequencies transmitted. If an audio frequency range extending to 5,000 cps is transmitted, the sidebands will similarly extend to 5,000 cps either side of the carrier, and the station will have a channel width of 10 kc.

In FM, the sidebands also determine the frequency spread of the transmitted signal. As in AM, the frequency spread of the FM

carrier and its sidebands at any instant depends on the frequency of the audio signal at that instant: however, *the frequency spread also depends on the amplitude of the audio signal at that instant.*

Let's consider first what the amplitude of the audio signal has to do with frequency spread.

If the intensity of an audio signal is increased at the transmitter, the number of important sidebands increases (see Fig. 36-11); that is, sideband frequencies whose power was previously negligible, become large enough to be important. This should help us understand what is meant by the statement *the greater the amplitude of the modulating signal, the larger the frequency deviation of the modulated carrier*. When the number of significant sidebands increases because of an increase in the amplitude of the modulating signal, a larger portion of the FM station's assigned spectrum space is occupied. When the amplitude of the audio signal drops, the number of sidebands decreases, and the spectrum space occupied by the carrier and its sidebands decreases. Note, in Fig. 36-11, that there is a separation of 15 kc between each sideband signal and the signal next to it, since the frequency of the modulating signal is 15 kc.

To clarify what the *frequency* of the modulating signal has to do with the spectrum space occupied by the transmitted FM signal at any instant, let's assume that a certain modulating signal causes three sidebands to be generated. If the signal has a frequency of 1,000 cps, the spectrum space covered by the sidebands will extend 3,000 cps either side of the carrier (see Fig. 36-12a) or a total of 6 kc. If the frequency of the modulating signal changes to 10,000 cps, but the number of sidebands remains the same, the frequency spread will extend 30 kc either side of the carrier, or a total of 60 kc (see Fig. 36-12b). In one case, then, the frequency spread is 6 kc; in the other, it is 60 kc.

If the number of sidebands generated depended only on the amplitude of the

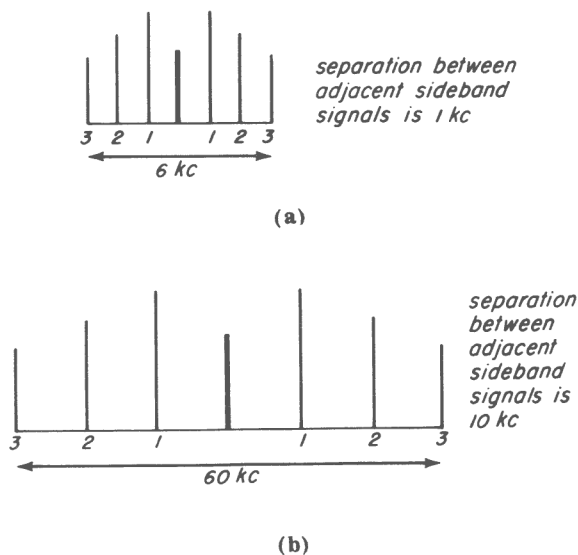


Fig. 36-12

modulating signal, and we knew the frequency of the modulating signal, we would readily be able to determine the bandwidth requirements. The number of sidebands, however, depends on the frequency as well as the amplitude of the modulating signal. *Assuming that the amplitude of the modulating signal remains unchanged, the lower the frequency of the modulating signal, the greater the number of sidebands that will be created.*

To summarize:

1. The frequency spread of a modulated FM carrier at any instant depends on the frequency of the modulating signal, as well as the number of sidebands produced by the modulating signal.

2. The number of sidebands produced by the modulating signal depends on the amplitude and frequency of the modulating signal.

A formula that relates these facts is:

$$\text{modulation index} = \frac{\text{frequency deviation}}{\text{audio frequency}}$$

where:

frequency deviation = deviation produced by the amplitude of the audio signal.

audio frequency = frequency of the modulating signal producing the deviation.

The number of significant sidebands present at any instant varies directly with the modulation index. The higher the modulation index, the greater the number of sidebands present, and vice-versa. Table A lists the number of significant sidebands present at various values of modulating index.

The modulation index helps us determine how much spectrum space will be occupied by the transmitted FM signal *at any instant*, with a modulating signal of a given frequency and amplitude. But we want to know what the *maximum* spectrum space occupied by the modulated FM carrier will be, because this determines the receiver bandwidth requirements.

The number of sidebands produced by an audio modulating signal depends both on the amplitude and frequency of the modulating signal. An audio signal of the highest frequency will produce a greater frequency separation between sidebands than any signal of a lower frequency, provided the amplitudes of the signals are the same.

Let's assume that a signal of the highest transmitted audio frequency (15 kc) is sent out at the maximum amplitude permitted. *Such a signal is capable of producing a greater frequency deviation than a signal possessing any other possible combination of frequency and amplitude characteristics.*

A maximum-amplitude 15-kc audio signal will produce a carrier deviation of 75 kc, or a swing of 150 kc — the maximum allowed under FCC regulations. The modulation index under such conditions will be:

$$\frac{75 \text{ kc}}{15 \text{ kc}} = 5$$

This value of modulation index is a special one that is referred to as the *deviation ratio*. *It represents the value of modulation index that will produce the maximum permissible frequency deviation in broadcast FM.*

Now, a maximum-amplitude, 15-kc modulating signal that has caused the modulated carrier to deviate 75 kc from its resting fre-

TABLE A	
Modulation Index	Number of Pairs of Significant Sidebands
1	2
2	3
3	4
4	5
5	7
6	8

quency will produce significant sidebands that extend beyond the assigned 150 kc bandpass. How far will these sidebands actually extend? Well, inspection of Table A tells us that for a modulation index of 5 (which is the index the modulating signal will have under the conditions specified), seven significant sidebands will be created. Seven sideband signals spaced at 15-kc intervals will produce a deviation of 105 kc either side of the carrier, or a band spread of 210 kc. The assigned FM channel extends only to 150 kc. But the sidebands will not cause interference to an adjacent channel. The reason is that *guard bands* are provided at either end of an FM channel. These guard bands prevent significant sidebands from falling into adjacent channels. The guard bands for each channel extend 25 kc beyond either end of the channel (see Fig. 36-13). Considering the guard bands as part of a channel, each FM station occupies 200 kc (Fig. 36-14).

The seventh set of sidebands of the signal we have just discussed will not produce interference in adjacent channels because this set falls into the guard bands of the adjacent channels, and because the amplitude of this seventh set is very small.

A high-frequency signal of 15 kc is rarely, if ever, transmitted at maximum amplitude. Since signals that represent other combinations of frequency and amplitude will not produce sidebands that cover as

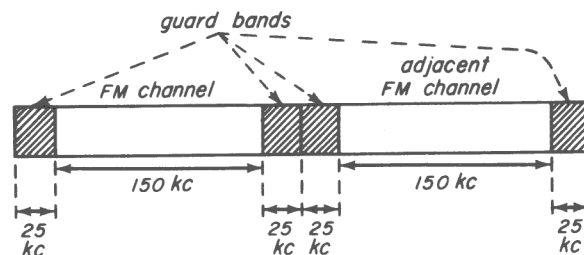


Fig. 36-13

much channel space as the signal just considered, interference between channels because of overlapping sidebands is not a problem.

36-6. ADVANTAGES AND DISADVANTAGES OF FM VERSUS AM

FM has a number of advantages over AM. These advantages are as follows:

1. FM receivers are much less affected than AM sets by atmospheric and man-made noise.
2. FM sets have a lower level of background (receiver-caused) noise.
3. The efficiency of an FM transmitter is greater than that of a comparable AM transmitter.
4. FM sets are much less subject to interference than AM sets.

The chief disadvantage of FM is a condition called *multipath distortion* that affects reception in some areas. The condition will be described later on in this lesson.

Noise Reduction on FM. Noise comes from sources within the radio as well as outside it. The random movement of electrons in resistors, coils or wiring, is one source of noise. The tiny erratic changes in the plate voltage of a tube, produced by haphazard variations in plate current, comprise another source of noise. A certain amount of such noise-producing variation is inherent in plate current flow. The noise signals created by the conditions just referred to cover the entire radio frequency spectrum (zero frequency to the highest

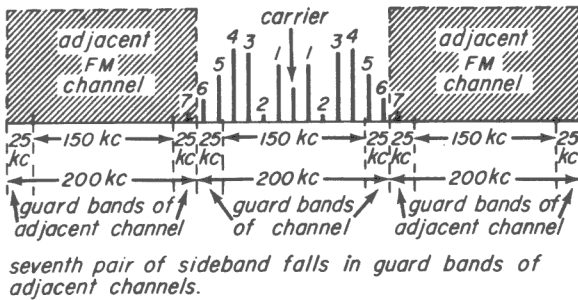


Fig. 36-14

measurable frequency). Atmospheric noise, and man-made noise produced by the operation of electrical devices also create disturbances that extend over a wide portion of the radio-frequency spectrum.

In an AM radio, detected noise pulses that fall within the audio-frequency bandpass of the receiver produce audible sounds in proportion to their amplitude. If the noise signals in the receiver are high in amplitude, the sounds they produce will be loud. The frequency of a noise signal has basically nothing to do with its audibility; if the receiver response is perfectly uniform over the audio range, noise signals of any frequency in this range will be equally audible.

This state of affairs is illustrated in Fig. 36-15. The rectangle shows the response of an AM receiver with an audio bandpass of 30 to 15,000 cps to noise signals whose amplitude is the same as audio signals that produce 100% modulation of the carrier. Note that the response of the AM receiver to the noise is uniform. If such noise signals are received and detected, noise may blanket the audio bandpass.

Figure 36-15 compares the responses of AM and FM receivers to a type of noise known as *impulse noise*. Noise in this category is produced by sparks of high intensity, either natural or man-made in origin. Such sparks create a fundamental noise signal and a series of harmonic noise signals that extend from a frequency of zero cycles (a signal of zero frequency is a d-c signal) to the highest measurable frequency.

There is another type of noise called *random noise*. Random noise is created by the random movements of electrons in con-

ductors and tubes. Noise signals of this kind may be considered as the output of an infinite number of tiny generators. The frequency and phase of random noise voltages is entirely haphazard.

The random noise response of the AM vs. the FM receiver is similar to the one illustrated in Fig. 36-15. The ratio in which the FM receiver is superior to the AM set with respect to noise rejection is approximately the same as in the case of impulse noise.

In an AM system, the modulation of the r-f carrier by noise signals is similar to the modulation produced by audio signals. That is, the desired audio signal varies the amplitude of the carrier, and so does the undesired noise. It is difficult to design circuits capable of removing the one type of modulation, without affecting the other.

In FM, the very nature of the system discriminates against noise. Whereas in the AM receiver, the noise voltage output of the detector is proportional to the *amplitude* of the noise input voltage, in FM the detector output depends primarily on the frequency of the noise. The closer the frequency of the noise signal is to the frequency of the carrier, the smaller will be the noise output voltage it produces, and vice-versa. The reason for this is tied to the fact that low-amplitude audio signals produce small deviations in the modulated carrier; at the receiver's FM detector, small deviations in frequency must consequently cause low-amplitude variations at the output of the detector, to reproduce the original audio signal. Since a noise signal that is close to the carrier in frequency represents a small frequency deviation, it will produce a low-amplitude noise voltage at the output of the detector.

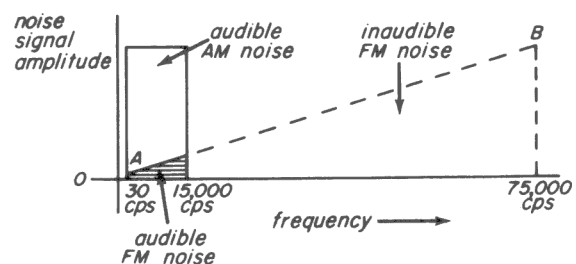


Fig. 36-15

Noise signals whose frequency is far removed from the carrier are similar to frequency deviations of the FM signal that are widely separated from the carrier. An FM signal whose frequency is far from the carrier represents a large-amplitude audio sound, and will cause a relatively large voltage output at the FM detector. Noise signals that are far removed from the carrier in frequency similarly produce substantial output voltages. The response of the FM system to noise may, in consequence, be represented as a triangle (see Fig. 36-15). The noise voltages produced at the output of the detector rise uniformly with the frequency separation of the noise signal and the carrier, causing the noise response to follow line A-B.

The maximum *audible* noise output of the FM detector is very small, compared to the maximum amplitude of the audio signal. The reason for this may be explained as follows: It takes a 75-kc deviation to produce an audio signal of maximum amplitude. A noise signal that is 75 kc away from the carrier cannot produce a comparably loud sound because the 75 kc beat signal that will be produced in the detector by the heterodyning of the noise signal and the FM carrier falls outside the bandpass of the audio stages.

Keep in mind that when an FM signal that is 75 kc away from the carrier heterodynes with the carrier in the FM detector, the detector output signal will vary at an *audio* rate. In the case of a noise signal that is 75 kc away from the carrier, however, the detector output signal will vary at a *radio-frequency* rate, and will therefore be inaudible.

The only noise signals that will be audible are those that are separated 15 kc or less from the carrier (at the input to the detector). Since the voltage output produced by a frequency deviation of 15 kc is quite small, compared to that generated by a 75 kc deviation (representing a maximum-amplitude audio signal), the percentage of maximum signal to maximum noise will be large—that is, the audio signal-to-noise ratio will be large—and noise effects will thus be minimum.

It is worth pointing out that when the maximum frequency deviation is smaller than 75 kc—as it is in the case of the FM sound channel of a TV transmission, where the permissible deviation is only 25 kc—the signal-to-noise ratio will be smaller, and reception of sound may not be as quiet.

The noise reduction that takes place in an FM set reduces the noise level to a value about $1/10$, or less, of the noise level in an AM receiver. This great difference in noise susceptibility is roughly indicated in Fig. 36-15. If you compare the AM rectangle and the FM triangle, you will note that the rectangle, representing AM noise, has a much greater area than the triangle, which represents FM noise.

Pre-emphasis and De-emphasis. Noise is further reduced in the FM system by the use of processes called *pre-emphasis* and *de-emphasis*. If you look at Fig. 36-15, you will see that the higher noise frequencies produce the greatest amount of noise. At the output of the detector in an FM receiver, noise frequencies close to but below 15,000 cps are the troublesome ones. However, such noise is attenuated through the insertion of a filter at the output of the FM detector. The filter is called a *de-emphasis network*. Figure 36-16a shows what the de-emphasis network does to the response of the audio section of the FM receiver. The reduced high-frequency response of this section causes high-frequency noise to be lowered in amplitude.

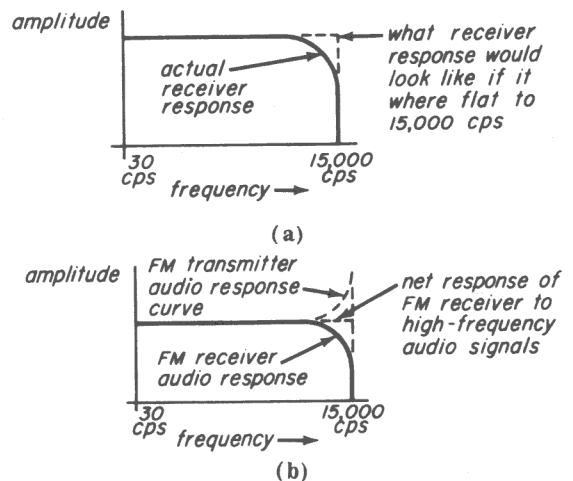


Fig. 36-16

The high audio frequencies as well as the high noise frequencies are cut down in amplitude as a result of de-emphasis. But these frequencies are transmitted at a higher-than-normal amplitude, or *pre-emphasized*. De-emphasis thus merely cuts them down to the correct original amplitude, and audio signals are uniformly amplified over the entire bandpass.

Figure 36-16*b* illustrates the over-all effect on high-frequency audio signals of pre-emphasis at the transmitter, and de-emphasis at the receiver. Note that the effects of de-emphasis and pre-emphasis cancel out, leaving the amplitudes of high-frequency audio signals unaffected. Since noise signals are *not* pre-emphasized at the transmitter, the reduced high-frequency response of the receiver cuts down their amplitudes.

Interference Rejection in FM and AM Receivers. In AM sets, an interfering signal that is only $1/100$ as large as the desired signal is capable of interfering with reception. In FM receivers, on the other hand, the interfering signal has to be *one-half as large* as the desired station signal for interference effects to be produced. The FM receiver, in other words, can effectively reject much larger interference signals than the AM set. Let's see why this is true.

In the case of an AM receiver, the mixing of an interfering station with the desired one will have the results illustrated in Fig. 36-17. The waveform produced by the heterodyning of the two signals varies in both frequency and amplitude. The ampli-

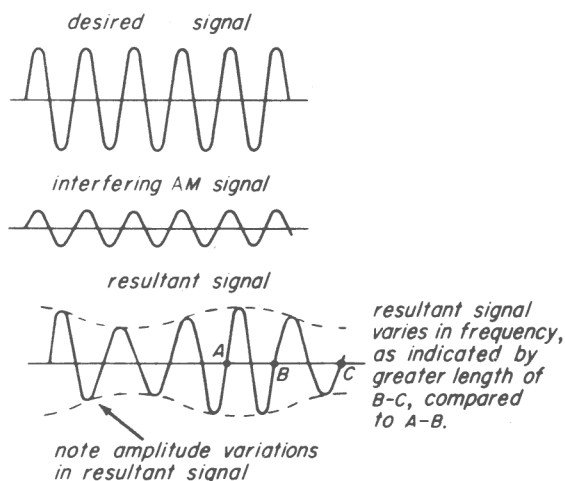


Fig. 36-17

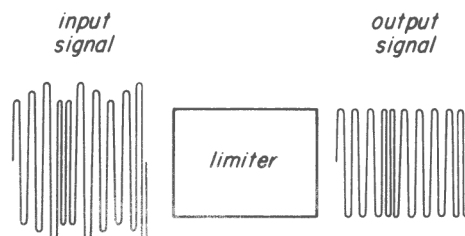


Fig. 36-18

tude variation will be detected and reproduced by the AM detector as interference. The magnitude or size of this variation depends on the ratio of the interfering signal to the desired one. If the interfering signal has an amplitude of 12 microvolts, and the desired station has an amplitude of 84 microvolts, the proportion of undesired modulation produced by the interfering signal will be 12 to 84, or approximately 15 percent. The interfering signal, then, will be 15 percent as loud as an audio signal that modulates the desired carrier 100 percent.

In the case of an FM receiver, the amplitude modulation produced by the interfering signal will not affect reception. This is so because the FM receiver is not sensitive to amplitude variations. A special stage called the *limiter* (see Fig. 36-18) removes such variations from the FM signal. (When there is no limiter, the FM detector employed is capable of rejecting amplitude variations of the FM signal.) It is permissible to remove amplitude variations from the FM signal because the audio intelligence lies only in its frequency variations. Amplitude variations *cannot* be removed from an AM signal because these variations contain the audio intelligence; removing them would eliminate the audio signal.

What we are concerned with, then, in the case of interfering signals in FM sets, is the amount of *frequency modulation* such signals produce. Now, the amount of frequency modulation created depends on two factors:

1. How big the interfering signal is compared to the desired signal.
2. What the frequency separation is between the interfering and desired signals.

Interfering signals are generally much

smaller in amplitude than the desired signal. The frequency modulation produced as a result of the amplitude of the interfering signal is therefore small enough to be neglected in most cases. What is important is the frequency separation between interfering and desired signals. Let's spend some time analyzing the interference produced because of this factor.

We saw in the case of noise that the amplitude of the noise-caused voltage variation at the output of the FM detector depends on the separation of the carrier and the undesired noise frequency. In the case of interference, the same holds true; the detector output again depends on the frequency separation of the carrier and the interfering signal. If the interfering signal is close to the carrier in frequency, the frequency deviations produced by the heterodyning of the interfering and desired signals will be small, and the detector output will be low; if the interfering signal is far from the carrier in frequency, the detector output will *tend* to be larger.

We say it will *tend* to be larger, because other factors will keep the output small. It was previously pointed out that the amplitude of the interfering signal determines, to a certain extent, the amount of frequency deviation that will be produced in the desired carrier signal. Now, if an interfering r-f signal is widely separated from the FM r-f carrier, the rejection action of the tuned circuits will keep the amplitude of the interfering signal low; the frequency deviations it produces in the modulated FM carrier will therefore tend to be small, and the detector interference output will be correspondingly low.

Since broadcasting stations operating on the same frequency are generally widely spaced from each other, the likelihood is that the undesired signal will come from a relatively distant source, and will therefore have a strength less than 1/10 that of the desired station in most cases. For the reasons we have just described in detail, the FM broadcast receiver is much less susceptible to interference than an AM set. However, in the case of mobile FM stations, such as taxicab radio or police radio, instances may often

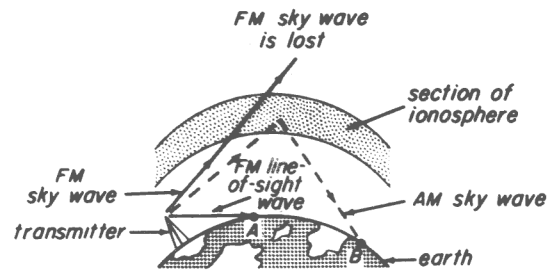


Fig. 36-19

occur where a strong but unwanted signal captures the receiver, and blocks out the weaker but desired signal.

FM Interference Due to Weather Conditions. FM signals fall in the 88 to 108 mc frequency range. Radio waves in this range travel in essentially straight lines, under normal conditions. This kind of transmission is called *line-of-sight* (see Fig. 36-19). It is characteristic of signals in the VHF and UHF bands. Since a line-of-sight distance is relatively short, long-distance transmission of VHF-UHF signals does not commonly take place.

Radiations from an AM transmitter that travel toward the ionosphere are reflected back to earth. Radiations from an FM transmitter that are directed toward the ionosphere are normally lost (refer to Fig. 36-19). In hot weather, however, or just before a storm, changes in the ionosphere permit the reflection of FM signals. Long-distance reception of such signals becomes possible in consequence.

When the interfering station is very close to the frequency of the desired one, and is the same or almost the same in amplitude, it will be heard in the FM receiver. If the strength of the desired and undesired stations fluctuate, so that first one then the other station becomes substantially stronger, reception of one station may alternate with the reception of the second. Under other conditions, both stations may be received simultaneously. Interference of this kind is infrequent. It is likely to last only a few hours.

Multipath Distortion on FM. A serious form of distortion that affects FM is called *multipath distortion*. This type of distortion can be produced when an FM signal arrives

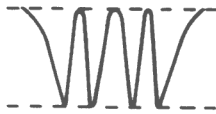
a constant-amplitude FM wave*amplitude-modulated FM wave*

Fig. 36-20

at the receiving antenna by more than one path. If the paths are different in length, the two (or more) signals arriving at the antenna, while identical in frequency and amplitude, will be different in phase.

The total signal input at the antenna is equal to the sum of these signals. If the signals are in phase at all parts of the cycle, they will add, and the net signal will merely become larger. When the phase of the signals is different, however, one signal may be rising in amplitude while another is falling, at a certain portion of the cycle. The signals cancel at such times. At some other portion of the cycle, when both signals are moving in the same direction, the signals will add. The net signal is distorted in consequence.

As a result of the addition of waveforms just described, the envelope of the net or resultant FM wave will vary in amplitude (Fig. 36-20). These amplitude variations may be so great that the FM limiter and detector are incapable of removing them. The signal output of the FM detector will be distorted in consequence (since it will detect and reproduce amplitude variations that are not present in the original signal).

Multipath distortion is chiefly a problem in areas where receivers are located fairly close to FM transmitters. It is most likely to be encountered in localities where there are tall buildings or other objects capable of reflecting or absorbing signals. Symptoms characteristic of multipath distortion include crackling, rattling, swishing or gurgling sounds. Sometimes, symptoms are noticeable on loud program passages only. In other cases, continuous and severe distortion causes the signal to become almost unintelligible.

36-7. FM RECEIVER STAGES

Now that we have learned something about the general aspects of the FM system, we can begin to discuss the FM receiver. A block diagram of a typical FM set is shown in Fig. 36-21. You can see that the FM receiver has many stages similar to those present in AM sets. These stages include the audio, i-f, front-end, and power-supply circuits. Stages that are completely different from those used in AM sets are: the limiter; the FM detector.

The operation of an FM receiver may be described in outline form as follows:

The incoming FM signal is picked up by the antenna and transferred to the first stage of the receiver. This stage is commonly an r-f amplifier; in some sets, it may be the converter. The r-f amplifier builds up the signal and helps establish a satisfactory high signal-to-noise ratio. The converter (or a separate mixer stage) mixes the r-f signal with the oscillator signal,

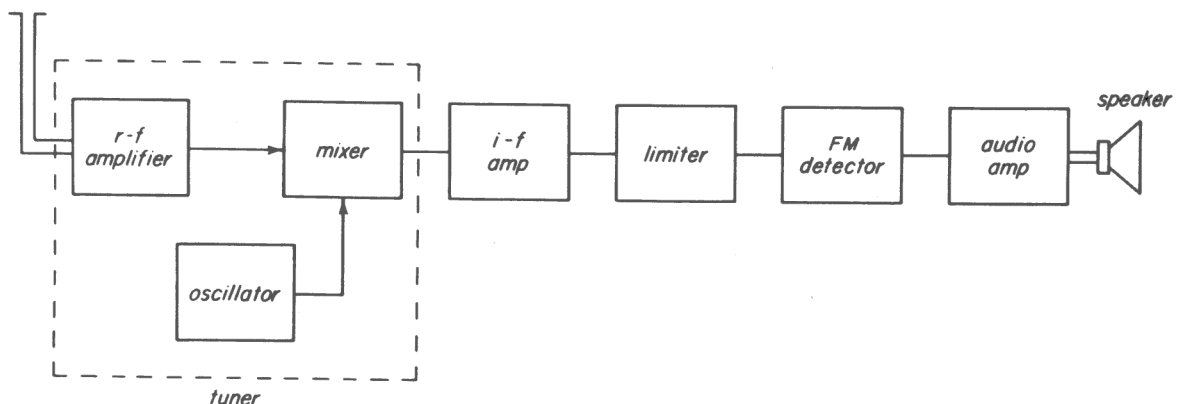


Fig. 36-21

just as it does in an AM superhetrodyne receiver. The output of the converter (or mixer) is applied to the i-f stages. These stages must provide sufficient amplification to saturate the stage that generally follows them: the limiter. The limiter removes amplitude variation from the incoming FM signal. Such variations represent spurious or undesired modulation generally produced by noise. If the limiter did not remove these amplitude variations, they could get through the FM detector and become audible in the speaker as noise.

For satisfactory limiter operation, the signal applied to the input of this stage must be adequately large (5 to 10 volts peak). This requirement makes a good antenna desirable; an adequate amount of i-f amplification also becomes necessary.

The FM detector is commonly either a *Foster-Seeley discriminator*, or a *ratio detector*. When a ratio detector is used, a limiter is not necessary because a ratio detector is capable of rejecting amplitude variations (provided they do not exceed a certain strength). When a Foster-Seeley discriminator is used, a limiter stage must also be used, since this type of detector is quite sensitive to amplitude variation in the incoming FM signal. Other FM detection systems are also found in FM receivers. These systems are described in the next lesson.

The FM detector converts the frequency deviations of the incoming signal into amplitude variations. These amplitude variations occur at the same rate as the frequency deviations of the signal, which, in turn, occur at the rate of variation of the original audio signal; the amplitude and frequency characteristics of the original audio signal are thus reproduced.

36-8. SIMPLE FM DETECTION SYSTEM

The discriminator, ratio detector and other FM detectors are quite complicated in their action. We are reserving a discussion of such circuits for our next lesson, in which various stages of the FM receiver

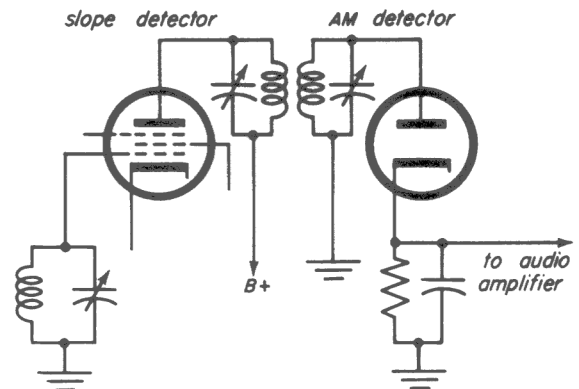


Fig. 36-22

are analyzed in detail. It will prove helpful, however, to discuss a simple means of FM detection at this time. Such a discussion will tie in with our preliminary survey of the FM system, and will complete the groundwork we have been laying for our future analysis of FM receiver circuitry.

Interestingly enough, AM receiver circuits can be used to detect FM signals. An AM i-f stage, and a conventional AM detector, may be employed for this purpose (see Fig. 36-22). The over-all circuit is called a *slope detector*.

The i-f transformer is tuned differently than it would be if AM signals were coming in. If AM signals were being received, the resonant circuit shown in Fig. 36-22 would be tuned to the frequency of the i-f carrier. For FM signals, however, the resonant circuit must be tuned so that the carrier arrives along the slope of one side of the curve. The resonant circuit is, in effect, detuned slightly from the carrier frequency, to achieve this.

If you remember your tuned circuit theory, you will recall that the voltage developed by a tuned circuit when a signal is applied to it depends on the frequency of the signal. If this frequency is the one to which the circuit is tuned, the voltage built up across the tuned circuit is maximum. If the signal is *above* or *below* the frequency to which the circuit is resonant, the voltage built up across the tuned circuit is less than maximum. The further away the signal frequency is from the frequency to which the circuit resonates, the smaller is the voltage that builds up in the tuned circuit. When the ap-

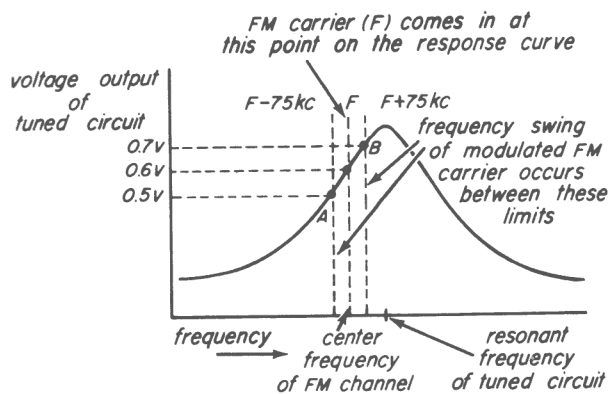


Fig. 36-23

plied signal falls far outside the bandpass of the tuned circuit, it will cause no signal voltage at all to build up in the tuned circuit.

This characteristic of tuned circuit operation is put to good use in slope detection. Remember, the basic requirement of an FM detection system is that it convert frequency variations into corresponding amplitude variations. Suppose the carrier frequency signal is coming in. The voltage built up across the tuned circuit will be, say, 0.6 volts (see Fig. 36-23). When the incoming FM signal deviates to a frequency higher than the carrier, the frequency of the signal will be closer to the one to which the tuned circuit is resonant; the voltage built up in the tuned circuit will therefore go up. When the FM signal deviates to a frequency below the carrier, it will move further from the frequency to which the tuned circuit resonates, causing the voltage built up in the tuned circuit to drop. Frequency deviations of the modulated FM carrier are thus converted into corresponding amplitude variations; these *amplitude variations* contain the audio intelli-

gence of the modulated FM carrier's frequency variations.

Now, the amplitude variations referred to are not— not yet, at any rate— audio signals. They are *amplitude variations of an i-f carrier and its sidebands*. These amplitude-modulated i-f signals must be demodulated. An AM detector performs this job, and recovers the audio intelligence.

The i-f transformer must be tuned— or rather, detuned— in such a way that the FM carrier and its sidebands are received along a linear section of the tuned circuit response curve. The small section A-B along the side of the curve (Fig. 36-23) is fairly linear. If operation took place along a nonlinear section of the curve, the amplitude variations produced would not be strictly proportional to the frequency variations, and distortion would result.

This type of FM detector is called a slope detector because detection takes place along the slope of the response curve. Such a system is not used in modern FM sets because slope detection is inefficient. The AM signal into which the frequency-modulated carrier is converted is capable of being only 18% amplitude-modulated, approximately. This means that a 100%-modulated FM signal is converted into an 18%-modulated AM one — a modulation loss of more than 80%. While the FM signal has been effectively cut down to about 1/5 of its strength, noise is permitted to come through without attenuation. A poor signal-noise ratio results. It is easy to see that the noise-reduction benefits inherent in frequency modulation cannot be obtained when a slope detection system is used.